EVALUATING FIXED WING AIRCRAFT IN THE AIRCRAFT CARRIER ENVIRONMENT

by

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Summary

Operating fixed wing aircraft from today's modern aircraft carrier is a demanding task. Evaluation of aircraft/ship compatibility, both during the concept development phase and Full Scale Development (FSD) ground and flight tests presents the evaluation team with unique challenges. The capabilities and characteristics of high performance carrier based tactical aircraft must be quantified for the catapult launch and subsequent flyaway, and the carrier approach and arrested landing tasks. Catapult launching involves determining the minimum safe launch airspeeds while maintaining acceptable flight characteristics in this low altitude, high angle of attack (AOA) regime. Approach and landing requires the slowest possible approach airspeeds while retaining the performance and handling qualities needed for precision glide slope control. Defining the lowest catapult launch and landing airspeeds reduces wind over deck (WOD) requirements, resulting in reduced ship's operating speed and increased operational flexibility. The tight operating confines of the flight and hangar decks, in conjunction with the large number of other aircraft, support equipment, and personnel dictate unique design requirements which must be considered in the earliest design stages of a new airplane. This paper addresses the shore based and shipboard ground and flight tests which are conducted to assess the flying qualities, performance, and structural suitability of an airplane in the aircraft carrier environment.

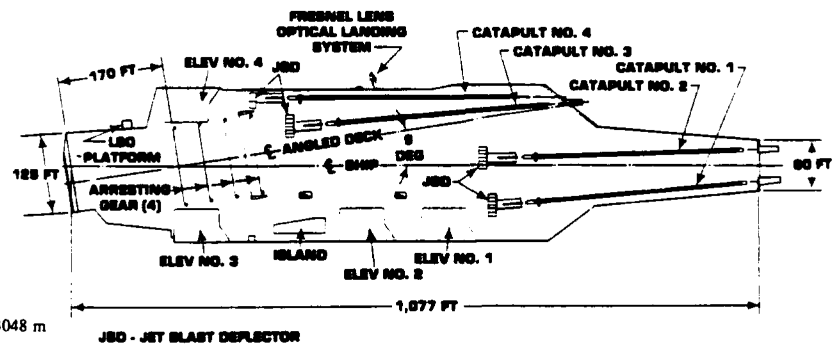
The Aircraft Carrier Flight Deck Layout

The flight deck layout of today's modern aircraft carrier is shown in figure 1. Two steam powered catapults are located forward (bow catapults) and two catapults are located amidships on the port side (waist catapults). Retractable Jet Blast Deflector (JBD) panels are located aft of each catapult. The centerline of the landing area is angled relative to the ship's centerline, permitting simultaneous catapult launch operations from the bow catapults and arrested landing operations. Four arresting gear cables, connected to arresting engines are located in the landing area. The first is approximately 170 ft (51.8 m) from the stern with approximately 50 ft (15.2 m) between each arresting gear cable. Visual glide slope information is provided to the pilot by a Fresnel Lens Optical Landing System (FLOLS). Aircraft are moved between the flight deck and the hangar deck by four elevators.

Catapult Launch

Evaluation of the catapult launch environment of an airplane covers many disciplines. These areas include:

a) Compatibility with the catapult accessories.



1 ft = 0.3048 m

Figure 1
Plan View of Flight Deck
NIMITZ Class Aircraft Carrier

b) Exhaust gas recirculation/reingestion and the thermal/acoustic environment when operating at maximum power in front of the JBD's.

c) Tolerance of the engines to ingestion of steam emitted from the catapult during the power stroke.

d) Structural integrity during the catapult power stroke.

e) Minimum catapult launch airspeeds and characteristics during the rotation and flyaway phases.

f) Shipboard catapult launch operations such as waist catapult operations, lateral/directional trim requirements for asymmetric external stores and crosswinds, etc.

Catapult Accessories

Catapult accessories are the items of hardware necessary to attach the airplane to the catapult. Items considered are:

a) Ease of installation of the repeatable release holdback bar on the nose gear.

b) Tracking of the launch bar tee head and holdback bar in the catapult nose gear launch guide rails.

c) Mating of the launch bar tee head with the catapult spreader.

d) Clearance between the airframe and external stores and above deck obstructions such as the catapult shuttle, catapult control station, etc.

e) Holdback bar dynamics following release due to the sudden release of high strain energy.

Jet Blast Deflectors

Exhaust gas recirculation and reingestion can occur when an airplane is operating at maximum power levels when positioned in front of the JBD. Reingestion of exhaust gas can cause an excessive temperature rise in both the compressor and turbine sections, resulting in damage to the engine. Ingestion of exhaust gas by the airplane positioned behind the JBD can also result in damage to it's engine. Impingement of the exhaust plume on the JBD panels can result in local hot spots which can cause premature warping and cracking. JBD operations can also result in a severe acoustic and thermal environment. Shore based tests are conducted using a shipboard representative JBD installation. Testing consists of placing one airplane forward of the JBD panels and a second airplane aft of the panels as shown in figure 2. The position of the airplane in front of the JBD is varied from the minimum to the maximum engine tailpipe to JBD distances representative of shipboard JBD/catapult combinations. Military and afterburner thrust (if available) runs are conducted for approximately 30 seconds. Both airplanes monitor engine inlet and exhaust gas temperatures and other critical parameters. The acoustic and thermal environment is monitored using microphones and thermocouples mounted on the airframe and in the vicinity of the JBD. Pole mounted instrumentation provides jet blast velocities and temperatures in the flow field beside and behind the JBD. Generally, the wind over deck during shipboard operations tends to alleviate any recirculation, reingestion, or thermal problems. However, if an airplane has demonstrated a tendency to have excessive exhaust gas ingestion, a shipboard test program may be warranted to define a wind over deck envelope which reduces the ingestion to acceptable levels.

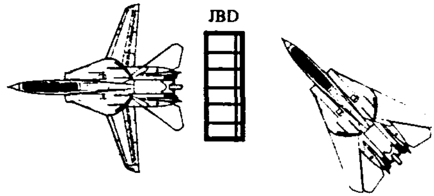


Figure 2
Airplane Locations
During JBD Testing

Steam Ingestion

Steam catapults typically emit launch steam above the deck during the launching operation. The design of the engine inlets and the proximity of these inlets to the catapult shuttle frequently cause this above deck steam to be ingested through the engine(s) of the airplane being launched. The result is that the engine is forced to operate at off-design conditions and instabilities can occur. These instabilities can take the form of minor pressure fluctuations within the compressor or the afterburner and could result in blowout, compressor stall, or engine flameout.

The primary method of determining susceptibility to stall is to conduct shore based catapult launches from a degraded catapult. The catapult is intentionally degraded by removing plugs in the aftermost plate of each piston assembly. This allows steam in the cylinders to travel forward of the aft face of the piston, bypass the catapult cylinder sealing strip as the shuttle assembly lifts the sealing strip during the power stroke, thus allowing the steam to exit above deck around the catapult spreader. This steam leakage produces conditions that are more severe than those encountered in the actual shipboard environment. The airplane is launched a sufficient number of times (about 30 launches) to reasonably ensure that no instabilities are encountered. An appropriate number of additional launches will also be required if the engine is equipped with an afterburner. Testing is confined to those days when the surface winds are less than 10 knots and ± 20 deg relative to the catapult centerline. Telemetered engine performance parameters are monitored to ensure continued satisfactory engine performance.

Structural Requirements

A typical catapult launch structural envelope is shown in figure 3. This figure shows the longitudinal acceleration (N_X)/launch bar load/maximum gross weight boundaries.

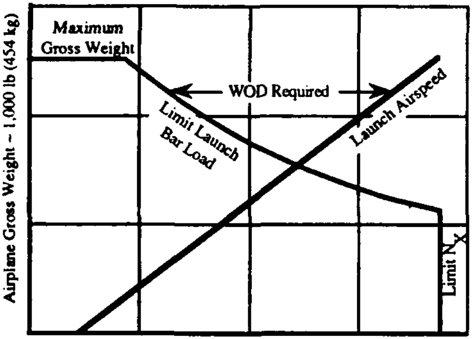


Figure 3
Typical Airplane/Catapult
Structural Envelope

The N_X and limit launch bar load limits are design numbers which are defined by the mission requirements and maximum performance capabilities of the catapult types from which the airplane is to operate. The maximum gross weight is an airplane design factor based on a 10% growth factor of the basic operating weight of the design. Shore based structural testing consists of increasing the catapult end speed until either the limit N_X or launch bar load is reached. Catapult tests involving a new airframe are initially conducted with full internal fuel loads only. As testing proceeds, additional external and internal stores are carried until all weapon stations have demonstrated adequate strength for catapult launch to the limits of the basic airframe. Most launches are conducted with the airplane oncenter; however, offcenter launches with the main landing gear up to 24 inches (0.61 m) offset from the centerline position are performed to evaluate structural loads resulting from yaw accelerations and airplane directional characteristics during and following launch. The airplane and suspended stores are extensively instrumented to monitor strains and accelerations for all critical structural areas. A new airplane catapult launch structural demonstration program may require up to ten loading configurations to adequately test the structure/functional integrity during catapult launch.

Catapult Launch Minimum End Airspeeds

The most extensive test program relating to catapult launch is the determination of the minimum catapult launch airspeeds. From an operational point of view it is desirable that a minimum catapult launch end airspeed be defined. This minimum airspeed is the slowest equivalent airspeed achieved at the end of the catapult power at which the airplane can safely fly. Establishing the lowest possible launch airspeed has the following advantages:

a) Decreases the wind over deck required for launch, thus decreasing the ship's speed and increasing the operational flexibility of the aircraft carrier.

b) Decreases the loads imposed on the airframe increasing service life.

c) Decreases the amount of energy imparted to the airplane resulting in conservation of water and fossil fuel/core life.

The catapult launch minimum end airspeed is defined by a set of related criteria. Although these criteria generally have interrelated effects, the following addresses each factor separately:

a) Proximity to or warning of stall: The stall airspeed/angle of attack defines an absolute minimum. The required safety margin is dependent upon the characteristics of the airplane under consideration. If stall warning (generally in the form of artificial stick/rudder shaker and/or airframe buffet) occurs at some AOA below stall and the warning does not increase in intensity as the airspeed is decreased to the stall, then the angle of attack (AOA) corresponding to stall warning will likely define the minimum end airspeed.

b) Flying qualities/characteristics at high AOA: Frequently an airplane may exhibit adverse flying qualities or characteristics at high AOA, yet at airspeeds well in excess of the stall airspeed. The pilot must then determine the minimum airspeed/maximum AOA at which the airplane characteristics/flying qualities remain acceptable. Examples of limiting characteristics include: buffet, wing rock, wing drop, pitch up tendency, nonlinear stick force gradient, and unacceptable lateral/directional characteristics.

c) Proximity to the airspeed at which thrust available equals thrust required or "lockpoint": For practical purposes, the minimum launch airspeed should be at least 8 kt above the lockpoint. Pilots have indicated that the minimum level of longitudinal acceleration at which he has the sensation of accelerating is approximately 1 kt/sec. This level of acceleration must be available even though this airspeed may be more than 8 kt above the lockpoint. This acceleration capability must be available at the minimum end airspeed. This minimum launch airspeed may become the dominant factor at higher ambient temperatures due to the decreased thrust available with increased temperature. The maximum catapult launch gross of an airplane may be limited as a function of ambient temperature or the minimum launch airspeed may be increased to put the airplane on a more favorable position on the thrust required curve. Longitudinal acceleration characteristics can also be improved by reducing drag, such as using half flaps instead of full flaps or by the use of afterburner on airplanes so equipped. However, the use of reduced flap settings will increase the minimum launch airspeed and the use of afterburner greatly increases fuel usage during takeoff.

d) Airplane rotation requirements and subsequent sink off the bow: The postlaunch rotation requirement to achieve the flyaway attitude will frequently cause the minimum obtained to be higher than that predicted exclusively from proximity to stall or adverse flight characteristics. If the airplane attitude during the catapult launch differs significantly from the desired flyaway attitude, a lift deficiency exists during the period of time required to rotate the airplane. This causes the airplane to generate a sink rate and results in sink off the bow until airplane performance/aerodynamics provides sufficient vertical acceleration to establish level flight and subsequent flyaway. For a given airplane end airspeed, sink off the bow will vary with time required to rotate, average lift deficiency during rotation, and excess lift and thrust at the flyaway airplane attitude. Airplane CG sink off the bow of 20 ft (6.1 m) , as measured from the static position on the deck (CG vertical height), is considered the maximum acceptable.

e) Failure of one engine on a twin engine aircraft during launch: Two factors must be considered if an effort is to be made to establish a minimum end airspeed at which an airplane can remain airborne after losing one engine during launch. Foremost of these is the single engine minimum control airspeed (V_{MC}) at which sufficient control authority is available to counter the yawing forces. Secondarily, is whether the single engine rate of climb performance of the airplane is sufficient to permit safe flyaway. The single engine minimum control airspeed will establish an absolute minimum launch airspeed. If only a small increase in minimum end airspeed is required to improve single engine rate of climb performance enabling single engine flyaway, it should be a consideration in establishing the minimum end airspeed. The use of afterburner, if available, should significantly improve single engine performance, but will necessitate an increase in the minimum launch airspeed to provide single engine control.

f) Automatic flight control response: The incorporation of digital, fly-by-wire flight control systems into more recent aircraft models has eliminated the need for pilot programmed flight control inputs to attain a predetermined rotation and flyaway response. Current systems are implemented such as to achieve a desired flyaway trim AOA. However, flight control response due to pitch rate feedback during the highly dynamic conditions during the first several seconds following catapult shuttle release may result in flight control surfaces reaching their physical limits. If any of the primary flight control surfaces reach full deflection during the rotation or initial flyaway phases, the minimum end airspeed is then limited by this criterion.

Test Procedures

A considerable amount of time and effort is expended during shore based build-up to generate prerequisite data prior to tests aboard ship. Careful consideration is given to all the factors governing the minimum end airspeeds so that the results are applicable to the entire range of Fleet operating conditions. These factors include the high lift configuration (half or full flaps), external store loadings, CG positions, longitudinal trim requirements, and thrust (Military or afterburner).

Since the intent of determining the minimum airspeed is to define the lowest launch airspeed, the highest lift configuration is tested. With airplanes having more than one flap setting, the maximum flap deflection is suggested. However, this decision has to be tempered with the possibility of reduced nose up pitch authority which could result in increased time to rotate to the flyaway attitude, thus reducing sink off the bow. Additionally, there is an increased chance of reaching control surface limit deflections. The higher flap setting also results in more drag, thus decreasing longitudinal acceleration. External stores are selected to cover the range of anticipated gross weight, CG, and drag conditions expected during operational use. Forward and aft CG positions are tested to evaluate rotation characteristics and to define longitudinal trim requirements to be set prior to launch.

Shore based build-up flight tests are conducted in each of the high lift, external store, and CG position conditions. Classical flight test techniques are used to define the longitudinal/lateral/directional characteristics at high AOA up to stall, static/dynamic single engine control airspeeds, and thrust available and required. Shore based catapult launches are conducted at the predicted minimum end airspeed to investigate trim requirements, flyaway characteristics, and pilot technique. Shore based catapult launches are preliminary in nature because the airplane remains in ground effect and, of course, there is sink off the bow. All of these shore based tests enable prediction of the catapult launch minimum end airspeeds. The final judgement comes aboard ship.

Testing at Sea

The shipboard tests are conducted in a tightly controlled environment. Tests are conducted in steady winds from dead ahead and minimal deck motion. The catapult is maintained at a constant thermal state to ensure repeatability of catapult end speeds during subsequent launches. A calibrated boom anemometer is installed on the bow to provide accurate wind speed and direction. Noncritical external store loadings and CG's are tested initially. Initial launches are conducted well in excess of the predicted minimum airspeed (approximately 25 knots). Upon recovery following the launch the airplane is refueled and external stores expended prior to recovery are reloaded to re-establish the desired gross weight and CG. The catapult end airspeed is reduced in suitable decrements; initially 5 knots and then 3 knots as the predicted minimum end airspeed is approached. The initial reductions in catapult end airspeed are achieved by reducing the catapult end speed and as the predicted minimum end airspeed is approached, the catapult end speed is maintained constant and the wind over deck is lowered by reducing ship's speed. Airplane performance parameters; such as sink off the bow, rotation characteristics, flight control response, longitudinal acceleration, etc. are monitored and analyzed by the engineering test team via telemetered instrumentation. Catapult launch end airspeed is thereby reduced until one of the previously mentioned criterion are reached. This sequence of catapult launch tests are repeated for each critical gross weight, CG position, and external/internal store loading until the operational envelope has been defined.

In general, no minimum end airspeed criterion is the determining factor throughout the operational gross weight range of an airplane. An airplane may be V_{MC} limited at lighter gross weights, sink off the bow limited at medium gross weights, and longitudinal acceleration limited at high gross weights and ambient temperatures. Figure 4 represents these three different criteria.

It is important to note that the minimum catapult launch end airspeeds are the lowest airspeeds that an airplane can be safely launched. However, these airspeeds are determined under optimum conditions. These conditions include day VMC, a nonpitching deck, steady winds monitored by a calibrated anemometer, skilled aircrew trained in the optimum technique, gross weight and CG accurately known, catapult performance closely monitored, and end speed corrections made for ambient temperature and barometric pressure. In view of this, operational catapult launch operations are conducted at a recommended airspeed 15 knots above the minimum launch airspeed.

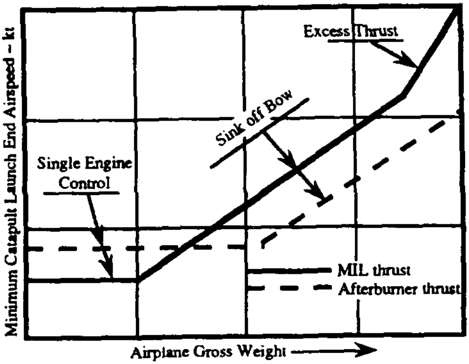


Figure 4
Factors Defining Catapult Launch
Minimum End Airspeeds

Although the shipboard test program to define catapult launch minimum end airspeeds involves the bulk of operations, other catapult launch tests are required. These include:

a) Waist catapult operations to assess the effect of the additional flat deck run forward of these catapults on the rotation characteristics and subsequent sink off the bow.

b) Lateral/directional trim requirements for asymmetric store loadings.

c) Crosswind launch operations, from both the bow and waist catapults, to determine lateral/directional trim requirements for crosswind components up to 15 knots.

d) Sensitivity of rotation characteristics and associated sink of the bow to improperly set longitudinal trim.

e) Light gross weight/low catapult end speed launches to evaluate the potential for degraded nose gear stored energy imparted pitch rates due to low catapult launch bar loads at the end of the power stroke.

Carrier Approach and Landing

The aircraft carrier approach and landing task is the most demanding task in aviation. The requirement is to maintain precise glide slope control to land in an area ± 20 ft (± 6.1 m) of the angled deck centerline and where the distance from the first arresting gear cable to the last cable is less than 120 ft (36.6 m). Control of both AOA and airspeed is demanded to remain with the structural limits of both the airplane and the arresting gear engines. This must be accomplished during both day and night operations and in all types of weather.

A typical Visual Meteorological Conditions (VMC) landing pattern for an aircraft carrier is presented in figure 5. Terminal glide slope information is provided to the pilot by a Fresnel lens optical landing system (FLOLS). For most recoveries, the glide slope is set for 3.5 deg. The approach is monitored onboard the ship by a Landing Signal Officer (LSO). The location of LSO and FLOLS is shown in figure 1.

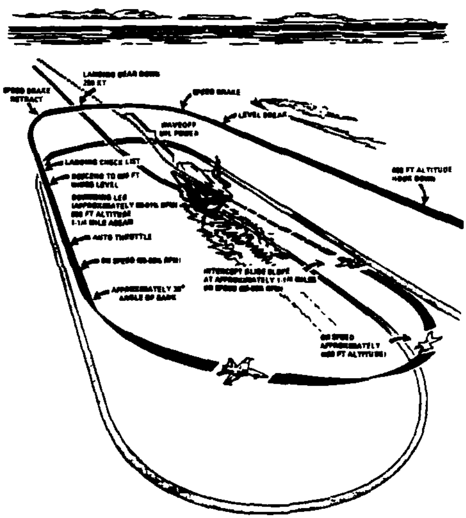


Figure 5
Typical VMC Landing Pattern

Extensive shore based approach and landing tests are conducted to determine the suitability of an airplane for carrier approach and recovery prior to initial sea trials. These tests include:

a) Structural integrity during landing and arrestment.

b) Optimum approach AOA and associated airspeeds.

c) Bolter and waveoff performance and characteristics.

Structural Tests

Landing an airplane aboard an aircraft carrier imposes severe loads on the landing gear and airframe. A flared landing is not performed. Immediately after landing, and sometimes before, the decelerating forces of the arresting engine are encountered. Last second glide slope and lineup corrections when encountering the turbulence induced by the ship's structure in combination with ship's motion can cause high airplane touchdown speed or rolled/yawed attitudes. Shore based arrested landing tests are conducted to evaluate structural integrity when landing in the many types of conditions possible aboard the carrier. These conditions are:

a) Maximum arresting gear engaging speed: This condition produces the maximum arresting hook loads and longitudinal decelerations and are conducted at the limit design condition of the airplane.

b) Rolled and yawed attitude at touchdown: This type of landing represents a last second lineup correction. The target attitude for both roll and yaw at touchdown is 5 deg. Landings are conducted with the roll and yaw in the same direction and also in the opposite direction.

c) Free flight arrestment: Occasionally an arresting hook will engage the arresting gear cable prior to main landing gear touchdown. This could happen with an inclose pitchup attitude change or during a waveoff. This type of arrestment is called a free flight. High nose gear landing loads are obtained upon touchdown. Free flight arrestments are intentionally conducted during the shore based test program.

d) Offcenter: All landings don't always occur in the center of the targeted landing area. Offcenter arrestments, up to 20 ft (6.1 m) left and right of the centerline are conducted to investigate the high side loads imposed on the arresting hook and airframe structure during this type of landing. The wing rock dynamics induced during this type of arrestment are monitored to determine any potential for contact of the wingtip or wing mounted external stores with the runway or arresting gear cables.

e) High sinking speed: To meet the design requirements for shipboard landings, U. S. Navy airplanes are designed for touchdown sinking speeds up to 26 fps (7.9 m/s). High sinking speed tests are the most critical of all the arrested landing structural tests. In the interest of safety, actual flight tests are conducted to 80% of the design limit. During testing, the targeted sinking speed is increased by slowly increasing the angle of the optical glide slope until the targeted sinking speeds achieved. In addition, this sinking speed is required to be tested at three different airplane pitch attitudes; 1) the normal landing attitude, 2) nose down (three point landing or nose gear first), and 3) a taildown attitude 3 degrees *higher* than the normal landing attitude.

The above five landing conditions are repeated in each of the critical loading combinations that the airplane will experience operationally.

<u>Approach AOA and Airspeeds</u>

Many factors must be considered relating to the determination of the recommended approach AOA and the associated airspeeds for the range of recovery gross weights. It is desired that the slowest possible approach AOA and airspeed be defined in order to minimize recovery WOD requirements. However, the need to establish the slowest AOA must be weighed against the requirement to ensure adequate flying qualities and performance to safely perform the carrier landing task. To this end, a number of criteria, mainly quantitative, have been developed to enable evaluation of the approach AOA and airspeeds. These criteria are part of the performance guarantees specified in the requirements for new aircraft. Attaining these criteria "should" ensure satisfactory carrier approach flying qualities and performance characteristics. For an airplane in the landing configuration on a 4 deg glide slope on a 89.8°F (32.1°C) day and at the carrier landing gross weight, the minimum useable approach airspeed (V_{PA}) should be the *highest* of the airspeeds required to meet the criteria detailed in the following paragraphs.

Acceleration Response to Large Throttle Inputs: For a large throttle input, such as a waveoff, the slowest airspeed will be that airspeed at which it is possible to achieve a level flight longitudinal acceleration of 5 fps^2 ((1.5 m/s^2) within 2.5 seconds after throttle movement. If any flight control effectors or speed brakes are automatically scheduled with throttle movement, then these surfaces may be moved. It is important to note that this requirement does not imply that the airplane must be in level flight with an acceleration of 5 fps^2 (1.5 m/s^2), rather that, during the approach, the engine(s) be operating in a region such that the acceleration characteristics would enable the engine to accelerate from the thrust required on glide slope to that thrust level equalling 5 fps^2 (1.5 m/s^2) acceleration at the same airspeed in level flight.

Acceleration Response to Small Throttle Inputs: The second approach airspeed criterion relating to acceleration capability is rapid engine response to small throttle movement. At the approach airspeed, step throttle inputs corresponding to a 3.86 fps^2 (1.18 m/s^2) longitudinal acceleration command will result in achieving 90% of the commanded acceleration within 1.2 seconds. This requirement applies both to acceleration and deceleration. This requirement applies throughout the weight range and anticipated drag levels of the airplane. Figure 6 shows this requirement.

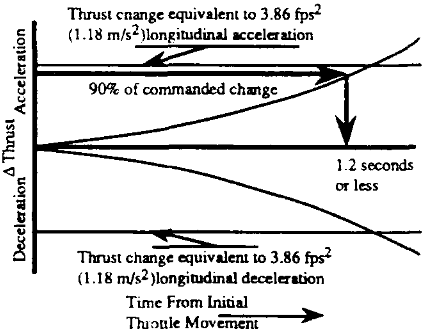


Figure 6
Acceleration Response
to Small Throttle Inputs

Over The Nose Field of View: The slowest acceptable approach AOA must provide adequate over the nose field of view. With the airplane at an altitude of 600 ft (182.9 m) above the water in level flight and with the pilot's eye at the design eye position, the waterline at the stern of the ship must be visible when intersecting a 4 degree optical glide slope. The source of the optical glide slope is 500 ft (152.4 m) forward of the ramp of the ship and 65 ft (19.8 m) above the water.

Margin Over Stall: The slowest airspeed equating to 1.1 $V_{S_{PA}}$, where $V_{S_{PA}}$ is the power-on stall airspeed using the power required for level flight at 1.15 V_{S_L}, which is the power-off stall airspeed. The determination of this airspeed is to first calculate V_{S_L}, calculate the power required to maintain unaccelerated level flight at 1.15 V_{S_L}, determine the power-on stall airspeed at this power level, then calculate 1.1 $V_{S_{PA}}$.

Flying Qualities: The slowest approach airspeed shall provide Level I stability and flying qualities.

Glide Slope Transfer Maneuver: This requirement is often referred to as the 50 ft (15.2 m) pop-up maneuver. The airplane is to perform a glide slope maneuver so as to transfer from one glide slope to another glide slope which is 50 ft (15.2 m) above and parallel to the first glide slope. The 50 ft (15.2 m) transfer is referenced to the CG of the airplane. The maneuver must be completed within 5.0 seconds. Longitudinal control can be inputted as necessary with the constraint that the maximum incremental load factor cannot be greater than 50% of that available at the start of the maneuver. The throttle setting cannot be changed during the maneuver. This maneuver is often misunderstood to mean that the altitude of the airplane is increased. In fact, the altitude at the end of the maneuver can be somewhat below that when initiated. For example, if the sink speed of the airplane is 15 fps (4.6 m/s) at the start, the airplane will intercept the new glide slope 25 ft (7.6 m) lower in altitude than when the glide slope transfer was started [15 fps (4.6 m/s)x 5 sec - 50 ft (15.2 m) = 25 ft (7.6 m)]. Once the new glide slope has been intercepted, longitudinal control and throttle inputs can be made to establish a new glide slope parallel to and at least 50 ft (15.2 m) above the initial glide slope. Figure 7 presents this maneuver.

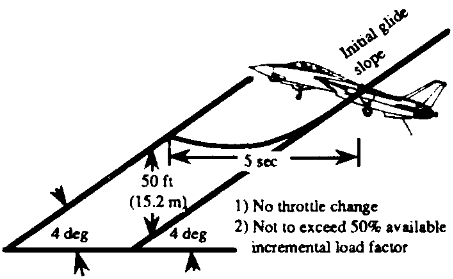


Figure 7
Glide Slope Transfer Maneuver

Additional Considerations:

Single Engine Control Airspeed: For a multi-engine airplane the slowest approach airspeed will not be less than the single engine control airspeed (V_{MC}). This will ensure adequate control in the event of a total engine failure during a waveoff when performed at the approach airspeed.

Touchdown Attitude: Touchdown attitude considerations have on occasion dictated the selection of an approach airspeed/AOA. The pitch attitude must be such that a tail down, free flight, or nose down arrested landing with resultant airframe damage be only remotely possible.

Glide Slope Tracking: The combination of airframe/engine performance is of prime importance in evaluating the handling characteristics of an airplane on the glide slope. The speed/power (or flight path) stability characteristics of an airplane have a great deal of influence on the ability of the pilot to make corrections in airspeed and rate of descent.

The following glide path correction capabilities are considered over the approach airspeed/AOA range:

a. The ability to make glide path corrections by changing the rate of descent at a constant thrust setting.

b. The ability to make glide path corrections by varying the thrust while maintaining a constant airplane AOA.

In making glide path corrections, the pilot instinctively attempts to do so initially with longitudinal control. Effective control of airplane pitch attitude necessitates that the longitudinal control power, damping, and mechanical characteristics be such as to permit small, precise pitch attitude corrections. It is extremely desirable that the airplane have maneuvering capability at a constant thrust setting for small changes in AOA on the order of one or two degrees. For making large corrections to the glide path which are sometimes necessary early in the approach, it is necessary to determine the change in thrust required for changes in AOA. An airplane that possesses this characteristic is easier to fly on the glide slope by correcting to glide slope with longitudinal control, returning to the proper approach angle of attack, and then adjusting thrust to correct for the original erroneous setting. Using this method, rapid glide path corrections are possible and thrust corrections in only one direction are required for each evolution.

If an airplane does not respond satisfactorily to longitudinal control, an alternate technique is evaluated. The airplane is maintained at the desired AOA and thrust corrections are used exclusively to make glide path corrections. With this technique, the airplane response as a function of the excess thrust available for maneuvering ($\Delta T/W$), the increase in thrust for small throttle movements, the engine acceleration characteristics, and the contribution of thrust to lift are all evaluated. Because of the lag in engine and airplane response to throttle movement and because of the tendency to "overcorrect" in order to establish vertical acceleration, it is difficult to determine the proper thrust setting required to hold the glide path. As a result, the pilot gets "behind" the airplane and the airplane follows a mild oscillatory path in the vertical plane of the glide slope. Therefore a procedure in which thrust and longitudinal control are initiated simultaneously is necessary for rapid corrections even though it requires precise coordination and increases pilot workload. The use of speed brakes may lessen the aircraft perturbations since increased power setting may provide better engine acceleration and the addition of any parasite drag device such as speed brakes contribute to speed stability by reducing the airspeed for minimum drag.

A combination of the numerous approach airspeed/AOA criteria dictates that the approach be made on the unstable portion (back side) of the thrust required curve. If an approach is made in this area, the use of the throttles is mandatory for making corrections in airspeed and rate of descent and thereby increases the difficulty of executing a precision approach. Further, if the approach must be made on the unstable portion, it is desirable that the thrust changes required are not large for small excursions from the approach airspeed. In terms of flight path stability, the change in flight path angle with airspeed should not be greater than 0.06 deg/kt. A rapidly increasing slope of the curve means that the airplane may decelerate rapidly and require the pilot to add much more thrust to stop a deceleration when compared to the thrust reduction necessary to stop an acceleration. It is also desirable that the approach be made where the curve has a gradient and not on the flat or neutral flight path stability portion where a range of airspeeds are possible for approximately the same thrust setting.

Lineup Control: Effective control of airplane heading is mandatory for carrier deck lineup control. Lateral control power, damping, and mechanical characteristics (trimmability, stick breakout forces, stick gradients, stick deadbands) should be such that the pilot can effect small, precise line up corrections during the approach. The use of lateral control should not cause distracting pitching or yawing moments.

The previous discussions have highlighted in general terms the numerous items which have a bearing on the selection the approach airspeed/AOA and an optimum pilot technique. Frequently, several flying qualities and performance characteristics become marginal at the same airspeed/AOA and one may mask another. It is important to recognize all of the factors involved since improvcments of one may render another more acceptable or unacceptable.

Qualitative Evaluation Tasks: In addition to the quantitative and qualitative evaluation techniques which are used in defining the approach AOA and associated airspeeds, it is possible to evaluate the approach and landing by defining the tasks the pilot must accomplish for each phase of the landing. Table 1 specifies the distinct phases during landing and lists suggested tolerance bands for the required performance. These levels of performance should be attainable with an HQR - 3 or better.

Table 1
Approach and Landing
Qualitative Evaluation Tasks

Phase	Task	Tolerance Band
Downwind	Airspeed Control Heading Control Trimmability	± 2 kt ± 2 deg ---
Base Leg	AOA Control Roll Attitude Control Heading Capture	± 1/2 deg ± 1 deg ± 2 deg
Final	AOA Control Lineup Control Glide Slope Control	± 1/2 deg ± 1 deg ± 1/2 "ball" (see note)
Touchdown	Runway Centerline Longitudinal Dispersion	± 5 ft (± 1.5 m) ± 20 ft (± 6.1 m)
Waveoff or Bolter	Attitude Capture AOA Control	± 1 deg ± 1 deg

Note: A "ball" is equivalent to one cell on the Fresnel Lens Optical Landing System. One cell equals 0.34 degrees of arc.

Waveoff Performance and Characteristics. A waveoff is a frequent occurrence in the shipboard environment and one which may be required due to the landing area going "foul" or not being ready to recover aircraft, unacceptable pilot technique, or conditions outside safe recovery parameters, such as excessive deck motion. A late waveoff is extremely demanding on airplane performance because of airplane sink rate and proximity of the ship. Flight tests are conducted to quantify airplane performance and determine the optimum pilot technique. This information is generated for both the normal recovery configuration(s) and all potential emergency modes, either airframe or engine related, for which shipboard recovery is possible.

Waveoffs are initially conducted at a safe altitude to assess airframe and engine response. The airplane is stabilized onspeed on a -3.0 deg flight path angle. Pitch tendency with power is noted. The landing configuration(s) and emergency conditions should be investigated. Simulated single engine characteristics and airspeeds, both static and dynamic, must be investigated prior to approaches at the field.

Two basic types of approaches terminating in a waveoff are investigated. They are:

a) Stabilized, on glide slope condition: This simulates a stabilized approach condition where a waveoff is required in response to an unsafe condition such as the deck going "foul". The airplane should be in a relatively stabilized condition at the approach AOA with the throttles at the approximate approach setting. To evaluate the variation of waveoff altitude lost and time required to achieve a positive rate of climb with sinking speed, the FLOLS basic glide slope angle is varied. In addition to onspeed conditions, AOA's as slow as 2 degrees higher than the approach AOA should be tested.

b) A high comedown condition: This condition represents a large throttle input by the pilot attempting to correct from a high (above glide slope) condition. The use of this "gross" correction technique will usually result in an immediate waveoff by the LSO. The test procedure should be to stabilize on glide slope, but holding a "one ball high" condition. At the desired time, the pilot retards the throttles to IDLE. From 1.0 to 2.0 seconds later, the waveoff signal should be given. This test technique has limited applicability within 1,000 ft of touchdown (a point approximately 500 ft (152.4 m) past the ramp) as this type of throttle "play" would result in an immediate waveoff being commanded by the LSO; however, this technique will identify unacceptable waveoff performance and excessive altitude loss due to adverse engine response characteristics.

Two pilot techniques for MIL thrust waveoffs are investigated. The first technique involves maintaining the approach AOA throughout the waveoff maneuver. The second technique involves rotation to higher values of AOA. *Level I flying qualities must be retained at all times during the waveoff.* Airplane pitch response to MIL thrust application and/or automatic configuration changes, such as speed brakes, may result in a slight uncommanded AOA rotation during the waveoff. This can be a favorable response in the noseup direction; however, is unacceptable in the nose down direction. Although rotation may minimize altitude loss, a point is reached near the ramp where rotation is undesirable due to reduction in hook/ramp clearance and the probability of a free flight engagement outside of the airplane design envelope. This undesirable characteristic is most noticeable for aircraft with large linear distance from the pilot's eye to the hook, such as the F-14A, where the vertical hook-to-eye distance increases approximately 1 ft (0.3 m) for each degree increase in pitch attitude.

The use of afterburner, if available, should also be investigated. Frequently, the time required to obtain MAX A/B thrust obviates its use to lessen the altitude loss during the waveoff maneuver. However, Max A/B thrust does provide an increase in acceleration once a positive rate of climb has been established and can avert a ramp strike for an airplane which has developed a high sinking speed prior to reaching the critical distance from the ramp. Average altitude loss determination for the various loadings and approach conditions should be based on at least twelve data samples because of differences in pilot techniques.

Fleet experience has shown that waveoff performance will be satisfactory if the following criteria is met from waveoff initiation during an approach on glide slope with the proper AOA and 0.7 sec pilot reaction time:

a) An hook point altitude loss not greater than 30 ft (9.1 m).

b) A time to zero sink speed not greater than 3 sec with a corresponding level flight longitudinal acceleration of 3 kt/sec on a 90°F (32.2°C) ambient temperature day.

c) A controllable aircraft pitch attitude change not greater than 5 deg airplane nose up or an AOA increase not more than 3 deg.

Bolter Performance and Characteristics. A bolter is an unintentional touch and go landing on the ship. A bolter can occur due to:

a) Improper in-close thrust or pitch attitude inputs or an excessively high glide slope position which result in the arresting hook point passing over the top of all the arresting gear cables. This is the more critical condition in that the minimum flight deck is remaining to execute the bolter maneuver.

b) The arresting gear hook point landing in the desired position, but the hook point failing to engage a cross deck pendant (CDP) due to: 1) hook point dynamics resulting in excessive hook bounce or lateral swing of the arresting hook shank preventing the hook point from engaging a CDP, or 2) improper tension on the CDP from the arresting engine allowing the CDP to be closer to the deck than desired limiting, the ability of the hook point to engage the CDP. In either case this is commonly referred to as a "hook skip bolter".

The distance from the last arresting gear cable to the angled deck round down varies from a minimum of 427 ft (130.1 m) on KITTY HAWK class ships to a maximum of 495 ft (150.9 m) on NIMITZ class ships.

Shore based touch and go landings are conducted to determine bolter performance, characteristics, and desired pilot technique. Landing sinking speeds at touchdown should be at least the mean carrier landing sinking speed to ensure that the airplane's pitch dynamics during the bolter, due to compression/extension dynamics of the main and nose landing gear, are representative of a shipboard landing. Flared landings will not produce realistic test conditions! All normal and emergency configurations should be tested. The forward and aft CG positions can be critical because of the potential effect on nosewheel liftoff airspeeds at forward CG's and adverse longitudinal characteristics at aft CG's.

The preferred method of obtaining bolter performance is to use LASER tracking data. The data is used for ground speed and ground roll only. Desired airborne instrumentation, in addition to the standard suite, includes nose and main landing gear weight on wheels (WOW) discretes which can be used to "time tag" their respective touchdown and liftoff times. The ground roll distances from main landing gear touchdown until nose landing touchdown, nose landing gear liftoff, and main landing gear liftoff are calculated from the LASER data. The calculated bolter distances are corrected for test day surface winds and then recomputed for anticipated recovery WOD in the shipboard environment.

The recommended pilot technique during these tests should be application of MIL power at touchdown and longitudinal control input as necessary to achieve the desired flyaway attitude. However, the use of full aft control can produce undesirable over-rotation tendencies. Other techniques should be considered if the characteristics of the airplane warrant.

It is desired that the airplane achieve both nose and main gear liftoff prior to rolling off the end of the angled deck round-down. However, if this condition is not achievable, it is still acceptable if there is no aircraft sink following rolling off the angled deck. Any CG sink is unacceptable. This requirement for no CG sink is based on a "normal" bolter. Situations will occur that will result in some CG sink. Delayed pilot response to the proper bolter technique of throttle and longitudinal control or initial landing gear touchdown well beyond the last CDP are examples.

The airplane pitch characteristics during the shore based bolter tests should be monitored. Landing gear dynamics can cause pitch oscillations (rocking) during the bolter. In an extreme situation, the airplane could be in a nose down pitch cycle when the nose gear rolls off the angled deck, resulting in unacceptable airplane characteristics and excessive sink following rolling off the angled deck.

Testing at Sea

Final determination as to the suitability of an approach airspeed/AOA, pilot technique, and bolter and waveoff performance and characteristics can only be obtained from actual tests aboard the carrier because of airflow disturbances over the landing area and aft of the carrier. Turbulence in the form of sudden updrafts and downdrafts which occur aft of a carrier cannot be duplicated ashore. The range of WOD's to be used should be from the minimum recovery headwind up to 40 knots, if achievable. Crosswinds components, both port and starboard, up to ship's limit (7 knots) should be investigated to evaluate the ship's island structure.

Initial approaches are terminated in waveoffs at approximately 1/2 nautical mile (1.9 km); the waveoff point is moved closer to the ship as test results merit. The first landings are "hook-up" touch and goes, finally with hook down to achieve the first arrested landing.

Intentional landings beyond the CDP's should be conducted to minimize deck remaining and time available to initiate bolter inputs, and also to evaluate rocking characteristics due to landing gear dynamics.